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GLOBAL NAVIGATION AND TRAFFIC CONTROL USING SATELLITES

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16. Abstract

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SUMMARY

A system approach is described which can support position determination, surveillance, and communications requirements of a large number of users. Position information can be computed and displayed at a traffic control center, and be transmitted to the users, together with traffic and hazard advisories, weather reports, and other messages. The system would also enable the user to compute his position independently on board. Digital communications at a rate of approximately 600 pps would be employed, while voice and higher data rate digital communications can be accommodated at the cost of increased satellite ERP.

INTRODUCTION

The Electronics Research Center of NASA has performed a number of studies in recent years, investigating the feasibility and utility of satellite systems for position determination of aircraft and ships. The feasibility of providing voice and data communications between low performance terminals and ground stations has been assessed as well. Such communications would be a necessary part of the traffic control system operation, and are of importance to company and management message traffic. Most user terminals will of necessity have low performance capability because of size and weight limitations on aircraft, as well as cost constraints on small vessels as applies to the fishing fleet (refs. 1-6).

Effort in this area has, in part, been motivated by developing problems with air traffic control in the North Atlantic Principal Area. A reduction in lateral lane spacing of North Atlantic aircraft will become necessary in the near future, or serious economic and scheduling penalties would result for the airlines. Increases in traffic density are anticipated which together with the introduction of SST service, will likely require reductions in lateral separations to the order of 30 - 45 n.mi. by the 1980 time period. Such a reduction will require significant improvement in both reliable, undelayed communications and accurate, frequent position determination. Table I depicts anticipated air traffic densities for the next several years. Of course, with increasing traffic densities over the world and the ability of commercial aircraft to carry many hundreds of people in one airplane, air safety, and collision prevention assume unprecedented significance.

At the present time, non-military aircraft makes use of various systems such as LORAN, Doppler, or Celestial navigation to obtain a position fix. Position information is forwarded to the proper traffic control center by h f ratio communication. This method of position reporting is marginally satisfactory for present day operation and will prove to be inadequate for projected traffic densities and lane spacings in future years.

There is a strong interest on the part of the airlines and regulatory agencies to provide a position determination which is "independent" of the system used to navigate the aircraft. This implies that the technique selected should not be strongly coupled to on-board navigational equipment, such that errors in that equipment could contribute in major proportion to total system errors. It also implies an approach which does not require human participation in the position report.

Figures 1, 2, and 3 indicate that present and projected ocean traffic densities are similarly alarming. Studies of marine shipping problems (ref. 1) show surprisingly high incidences of ship collisions and groundings (approximately 3000 per year) as well as recent upsurges in marine insurance rates. Costs of delays of ships carrying oil can in some cases result in losses of one million dollars per day. The ability to avoid groundings and collision of ships could prevent pollution disasters by oil or noxious cargo. With the advent of vessels of up to one million gross tons in the future, improved methods must be found to prevent collisions that could result in increasingly serious economic penalties.

A great number of applications of satellites exist which must be explored based on study results to date (Figure 4). These involve the use of satellite-derived data for collision avoidance, velocity determination, altitude determination, alignment and updating of inertial system, navigation, search and rescue, operational telemetry, and synoptic weather reporting.

The object of ERC's effort has been to develop a feasible design of a satellite system which could provide a durable solution to future air and marine position determination, traffic control, and communication needs on a worldwide basis. The system design is felt to be consistent with operational use in the 1980 time frame and beyond.

For position determination, position reporting, and collision warning, the feasibility is predicted with confidence. These functions should be performed in the L-band, a region where spectrum is still available between 1535 and 1660 MHz, and position determination accuracies can be achieved which exceed projected requirements. Figures 5 and 6 indicate the advantage of L-band frequencies over VHF in terms of ranging accuracy.

The system concept which has been identified makes use of present technology, with modest link power requirements and hemispherical coverage user antennas. The technique being considered can take advantage of future technology. Cost savings due to such improvements would be directly beneficial to users in the future as well as extend the classes of air and marine users which can afford to participate. Improved performance can likewise increase the base of applications.

The technical feasibility of voice and digital data communication is likewise projected with confidence. There is little question of the long-term desirability of performing voice and data communications at L-band, in view of the difficult spectrum problems in the VHF bands, although there is a cost penalty involved (Table II). The most promising solution to this problem (which could make L-band even less costly than VHF) involves the use of satellite antenna gains of the order of 35 - 40 dB. Design concepts for voice communications, positioning, and data communications systems are described in the following sections (refs. 7, 8, and 9).

VOICE COMMUNICATIONS

In order to provide efficient and economical voice communications at L-band, several requirements must be met (Figure 7). Primarily, rf power requirements, and consequently dc power requirements must be minimized. One way of reducing spacecraft power requirements is to increase spacecraft antenna gain; however, this can only be achieved by increasing aperture size, and consequently reducing earth surface coverage. This dilemma can be resolved by the incorporation of a steerable, phased array aboard the spacecraft; the gain requirements of approximately 35 dB are relatively modest, and the beam steering requirements of ± 8.5 degrees (in two dimensions) are well within the present state-of-the-art.

The antenna required for an L-band voice communications satellite may then be defined as a multiple-beam, phased array. A separate beam is provided for each channel. It is anticipated that three to six independent channels per satellite can be provided. Additional channels would be provided by additional satellites, as necessary, to avoid problems associated with mutual interference of the beams.

Each antenna beam will be provided with its own transmitter and receiver; the individual transmitter power level required is approximately 5 watts. Each beam will automatically acquire and track a specific user, either upon ground command, or by auto-track of a user pilot tone. The antenna requirements are defined in Figure 8.

It remains to demonstrate feasibility, since such an antenna has not yet been built and space-qualified. However, a very similar antenna is presently in the breadboard design stage for the NASA Data Relay Satellite; it operates at 2.2 to 2.3 GHz, and has similar design requirements to those stated above, with the exception that it is steerable over a ± 13 degree range, with 44 dB peak gain. It is anticipated that much of this technology will be directly applicable to the proposed L-band design.

Although development of such an antenna is forseen in the near future, a possible intermediate solution has been identified. This would require a single high-gain parabolic antenna, with multiple feeds. Each feed would provide coverage of 1/3 to 1/4 the North Atlantic Principal Path, with separate power amplifiers so that multiple channel coverage of any section would be achieved through use of an RF switch matrix. Such an antenna would require little new development, and would provide an ideal interim solution.

The spacecraft will be three-axis stabilized, in an equatorial synchronous orbit. Coverage is somewhat dependent on requirements; as an example, one such spacecraft, situated at approximately 30° West longitude, can cover the entire North Atlantic to approximately 70° latitude (and the South Atlantic as well, should coverage be required there).

Individual transponders will be provided for each spacecraft communications channel; to avoid interference they will utilize frequency division multiplex. Frequency assignments will be so chosen that transmit and receive bands are separated as far as possible, and clustered in the ends of the 1535-1660 MHz band.

In addition to voice, relatively wide-band (up to 2400 bps) digital data can be transponded. Proper design and use of the surveillance function will greatly reduce the anticipated voice communications load; judicious use of digital data for routine position and status information will reduce it still further. Because of the relatively high cost of a satellite voice link, the number of required links must be minimized; maximum use of digital data transmission wherever possible is one means to this end.

POSITIONING AND DATA COMMUNICATIONS SYSTEM

Characteristics of the satellite system for positioning and data communications have been identified and to some extent defined. Some important parameters cannot be fully assessed as yet, but it is possible to bound them. The size of the satellite will depend on the data communications requirements, since, f.i., communications bandwidth, and transmitter power determine size of solar and storage batteries which, in turn, reflect in spacecraft structure design and total weight in orbit.

The anticipated system of positioning and data communications satellites consists of a set of from ten to eighteen satellites in equatorial and inclined synchronous orbits. The orbits will be chosen over the entire globe for necessary coverage and geometry. Each satellite automatically radiates in time division multiplex, a carrier which contains ranging signals, followed by a data stream which provides ephemeris and timing corrections, ATC command, and/or advisory data. Each satellite contains a highly stable, crystal oscillator which serves as the time reference for the ranging signal. Satellite time and frequency synchronism are assured by constant monitoring at ground stations. Each ground station is associated with a master control center which transmits commands to the satellite as necessary. The satellite oscillator drift rate will be 1×10^{-11} per day or better; an oscillator update once every three hours will contribute approximately 30 meters of system bias error. This oscillator drift rate has already been achieved in orbit.

A specific time slot, then, is assigned to each satellite. This time slot lasts approximately 1.5-2 seconds, the exact timing depending upon the details of the final system configuration. Figure 9 is a timing diagram of the transmission sequence as presently envisioned.

Each satellite contains a number of registers which are loaded on ground command; these registers contain ephemeris data, timing, and oscillator information, and surveillance commands which appear at the end of each ranging transmission as a 625-bps data stream. Figure 10 is a block diagram of the position determination system.

The satellite signal is radiated on a carrier at a nominal frequency of 1540 MHz, at a power level of 50 watts into a despun earth coverage antenna, with a duty cycle of approximately ten to one. This provides sufficient signal strength at the user for an rms ranging error of 10 meters (Table III).

In its minimum form, the satellite would provide navigation and position reporting for air traffic surveillance. It would have sufficient downlink data capacity to warn aircraft of impending collision and provide maneuver instructions. This design could be accommodated on a satellite similar to Intelsat III. Estimates of the weight and power required for each major subsystem are identified in Table IV.

The user requires a hemispherical coverage antenna, with a gain of no less than 0 dB referenced to a circular isotrope for elevation angles greater than 20 degrees at all azimuths. A very promising candidate antenna and its pattern as measured on a scaled model are shown in Figures 11 and 12.

The signal is received in a preamplifier with a noise figure of 3.5-4.0 db, followed by a phase-locked receiver. The receiver, with a tracking loop bandwidth of approximately 50 Hz, performs the functions of carrier tracking, doppler removal, and coherent demodulation. One receiver output could be a signal whose frequency is a function of the relative velocity between user and satellite (coherent doppler extraction). The utility and necessity of such a signal remains to be determined.

The primary signal output consists of ranging and data signals as video outputs from the receiver demodulator. These signals are processed in separate ranging and data signal processors, whose outputs are effective range from user to satellite, and ephemeris data readout. This information permits the user to compute his position if desired.

Figure 13 is a block diagram of the user equipment required for surveillance or navigation. For an on-board determination of position, the surveillance data gate and transmitter would not be required and some form of computer and display system will be needed. The computer need not be a general purpose digital computer. Many aircraft and ships will have such a capability, however, allowing the possibility of on-board position computation at no additional cost on a time shared basis with other functions (Figure 14).

If surveillance is the primary function of interest, the computation and display requirements are unnecessary. This would be the mode of operation currently envisioned for oceanic air traffic surveillance.

Predominant interest lies in a surveillance system which is automatic and independent of on-board navigation equipment. To perform this function, a command is generated at the ground control center, stored in the satellite memory, and gated out synchronously with range tones and other data. Upon receipt of a satellite command, the user data processor energizes the user transmitter, and emits a burst of digital data (Table V).

At a bit range of 600 bps, the data transmission lasts for only one-third of a second. A lower power (~1 watt) transponder in the satellite relays the surveillance data to the ground control center.

For high fix rate requirements and to accommodate increasing numbers of users, multiple interrogations could be made sequentially after each satellite burst. Five interrogations would not affect cycle time or average power required for the satellite transmitter significantly and would provide one fix every 0.3 seconds. For 250 aircraft, this would allow an average fix interval of 75 seconds, which far exceeds expected requirements.

In order to provide for essentially simultaneous transponding from multiple aircraft, frequency division multiplex of user transmitter outputs is expected. For instance, if five commands are provided sequentially from each satellite, the specific interrogations from each satellite would be selected to address users which had had been assigned f_1 through f_5 before take off. All satellites in the system would carry low power (~1 watt) multi-channel repeaters. All returns would be repeated by all satellites providing a high degree of redundancy in the aircraft to ground link. High-gain ground antennas would receive only one satellite output, however, and reject all other satellite transmissions. In the event of the failure of any transponder, the ground antenna could simply direct its beam to another satellite for continued reception of user transmissions. This approach appears to provide a high level of redundancy and require a minimum frequency allocation consistent with interference-free operation. There is no significant additional satellite power required for either the satellite-to-aircraft or satellite-to-ground station links. The user uses the same receiver for interrogation as is used for ranging and data reception.

It will also allow, on a controlled access basis, additional data transmission from aircraft to ground with the same user transmitter and satellite transponder.

Capability of data communication on the down link may require some additional power on the satellite. However, this is easily available without changing the launch vehicle required. The satellite should be designed to take full advantage of the capability of the launch vehicle. In order to minimize recurring system costs, this is expected to be a Thor-Delta.

With the conventional Delta shroud, it appears that an upper bound on beginning of life power achievable with a spin-stabilized satellite will be the order of 300 watts. This would allow an additional transponder to be provided for down-link data communication on an earth coverage basis; of the order of one 600 bps data channel at 50 percent utilization per satellite. A preliminary estimate of the power and weight budgets for such a satellite is developed in Table VI. The satellite is limited by power availability rather than booster ability since some versions of the Thor-Delta are now capable of placing 575 pounds in synchronous equatorial orbit.

NASA has initiated the development of an 84-inch diameter shroud for the Delta in conjunction with the Canadian telecommunications project. Such a shroud will allow significantly higher power to be achieved. This, combined with possible increases in payload size and power if synchronous inclined orbits are selected, may allow greater data communication capability and a voice channel to be implemented on the satellite. If inclined orbits are selected close to 30 degrees, the apogee motor required will be significantly smaller than that required for synchronous equatorial orbit. Significant increases in the size and power available on such a satellite are expected over those identified in Table VI (ref. 10).

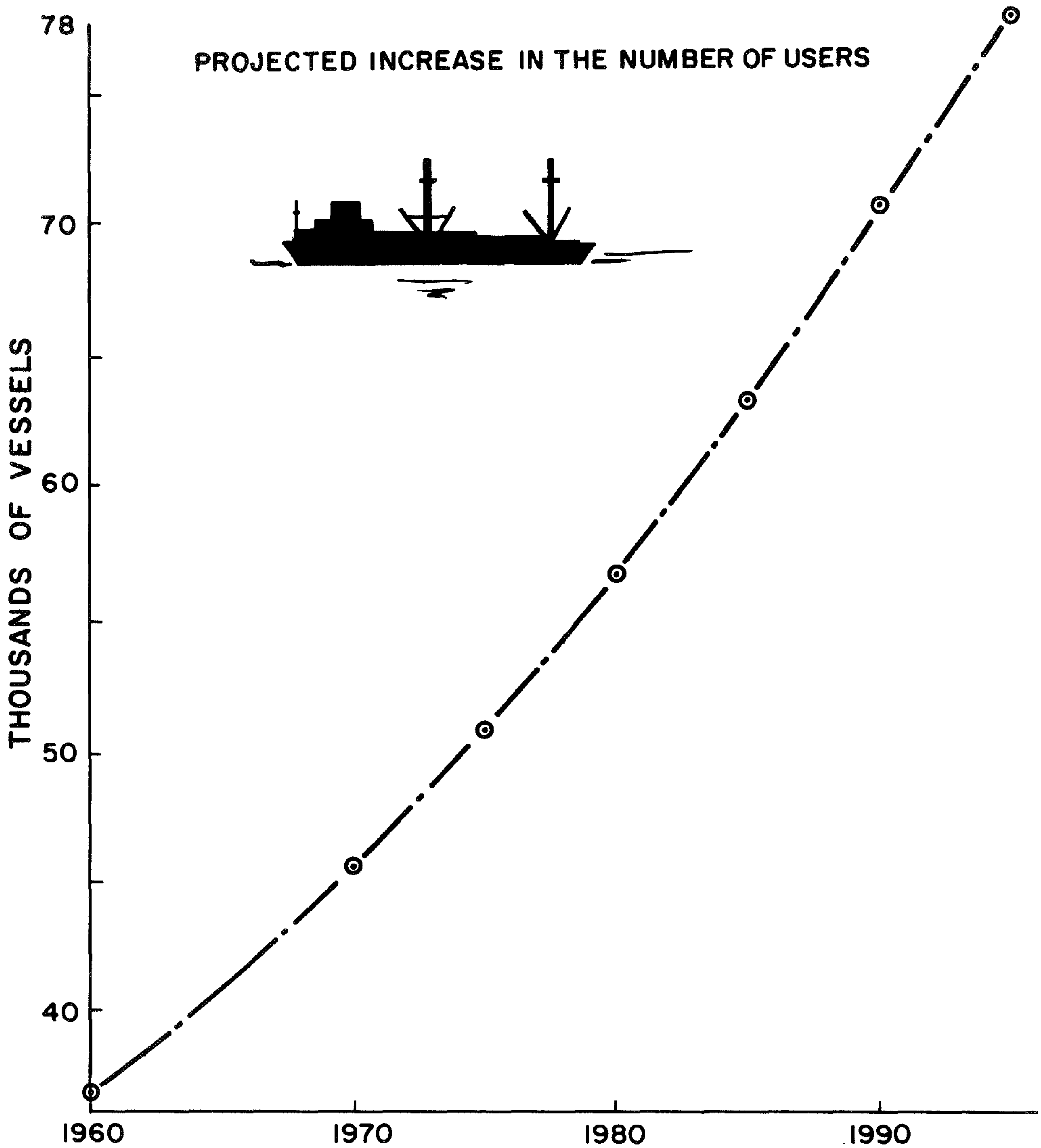

Figure 1.- Merchant fleet 100 gross tons and over

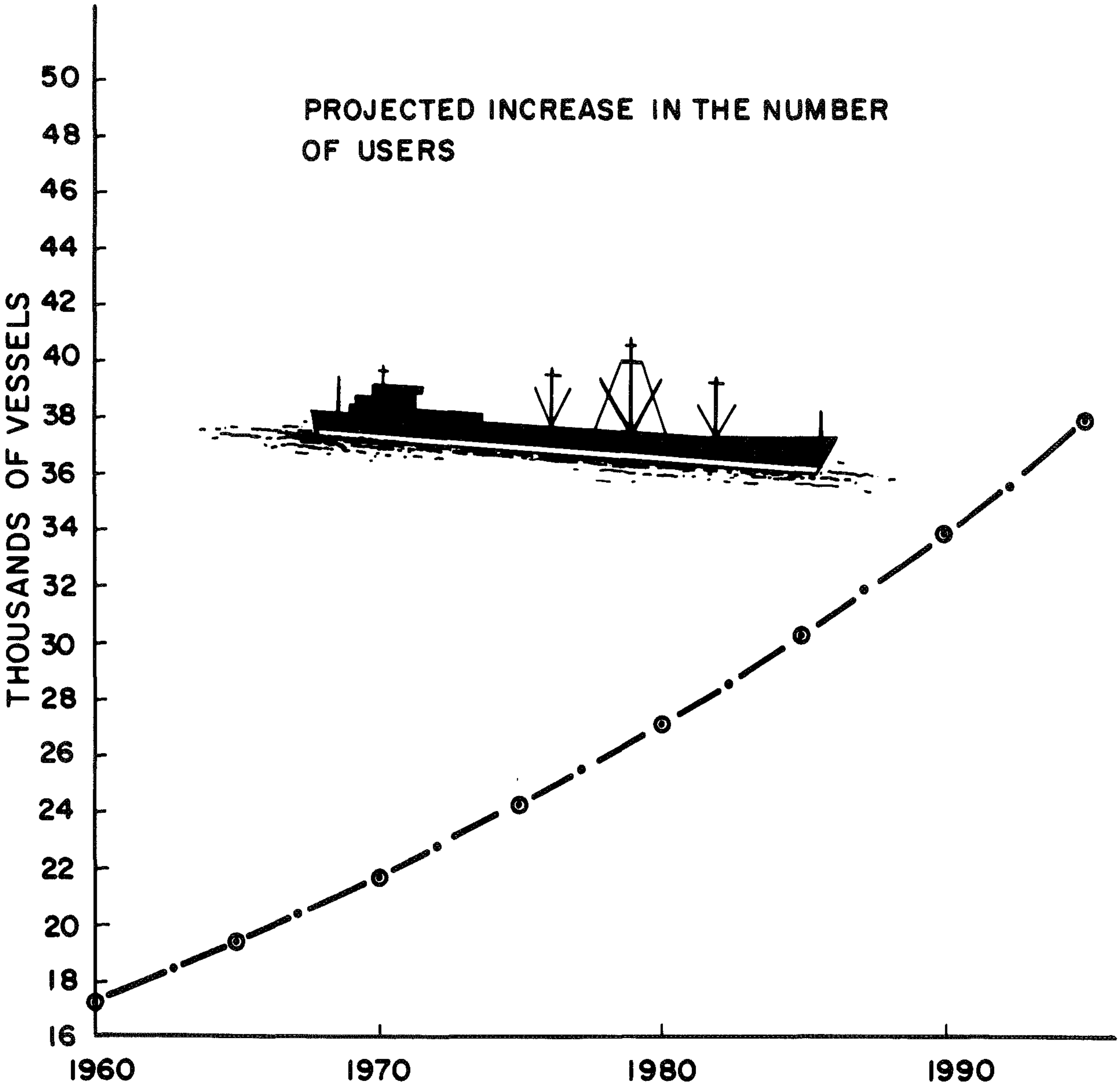

Figure 2.- Merchant fleet 1000 gross tons and over

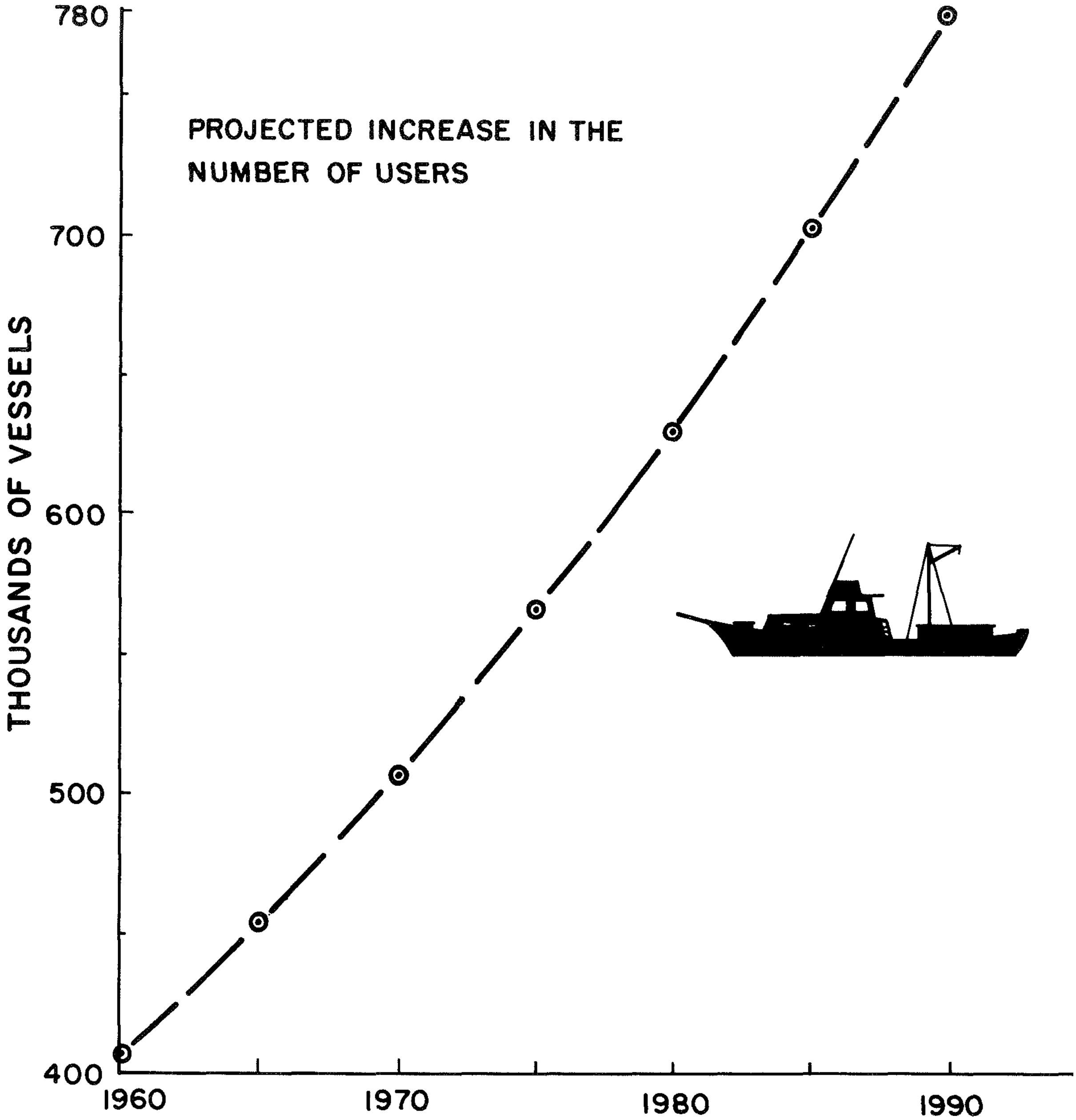

Figure 3.- Powered fishing fleet

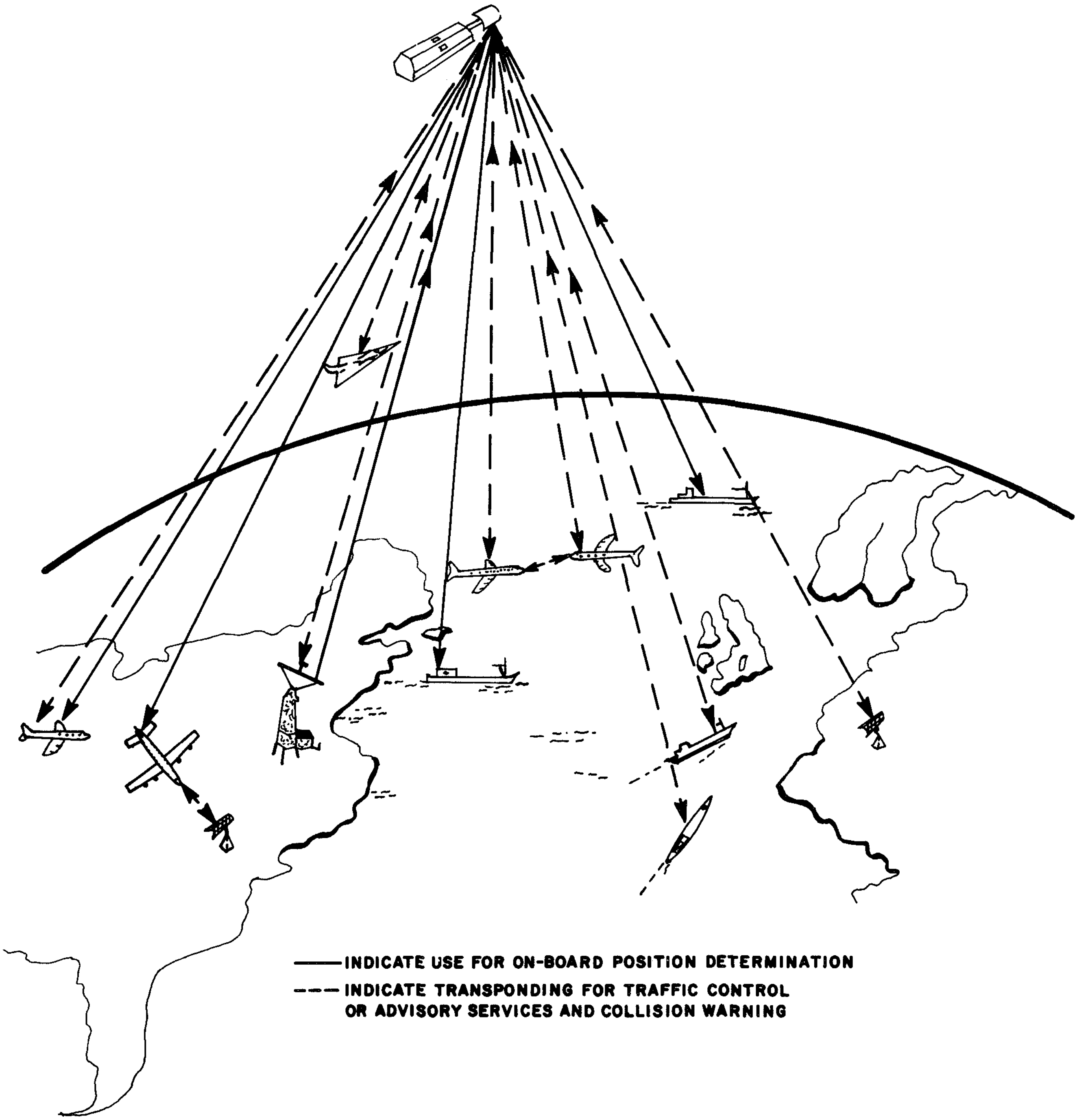

Figure 4.- Potential satellite applications

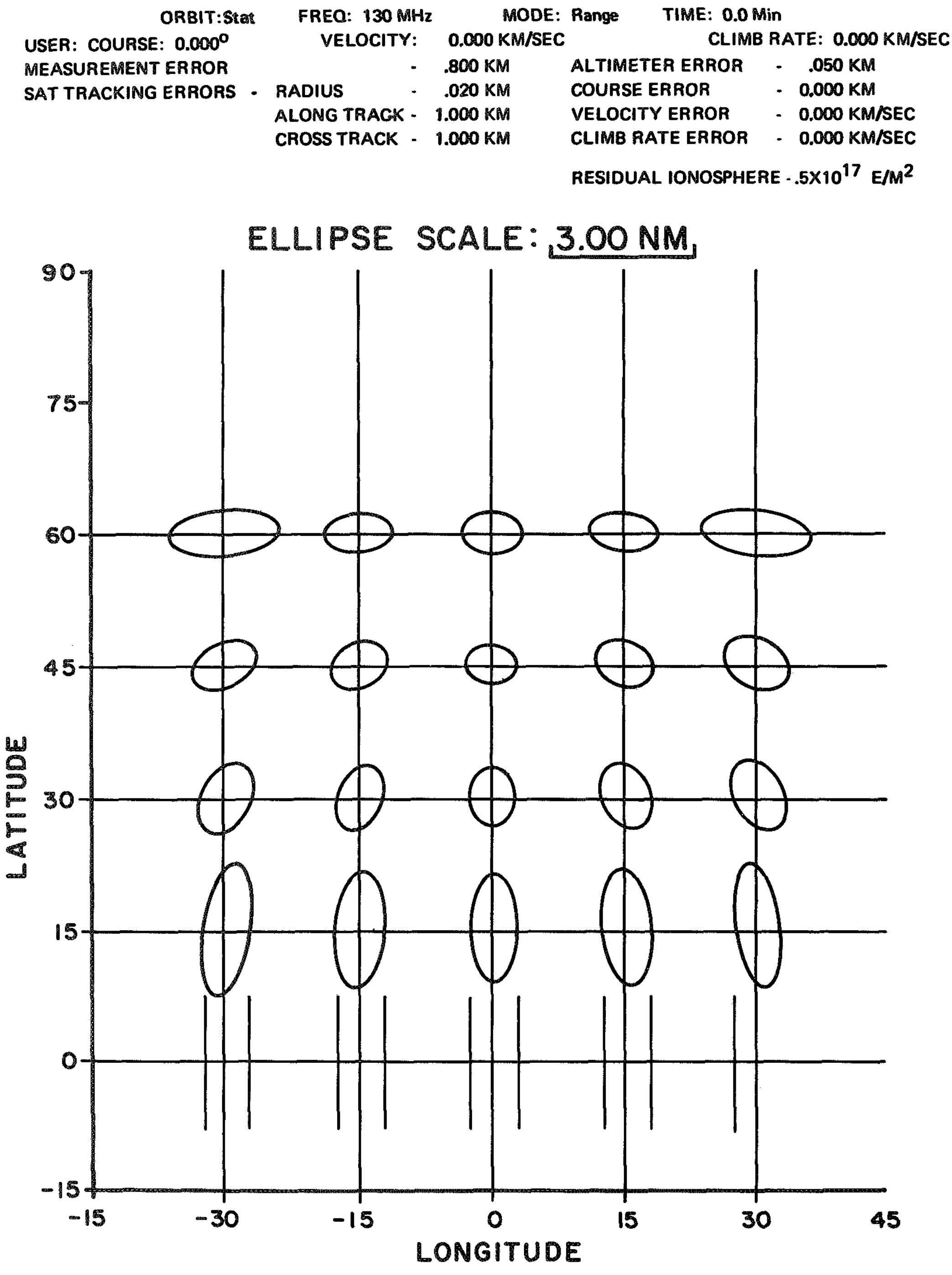

Figure 5.- Error ellipses for VHF spherical ranging for a corrected nominal afternoon ionosphere. Satellites in geostationary orbit with sublongitudes at ±30°. Error inputs are all 1σ values.

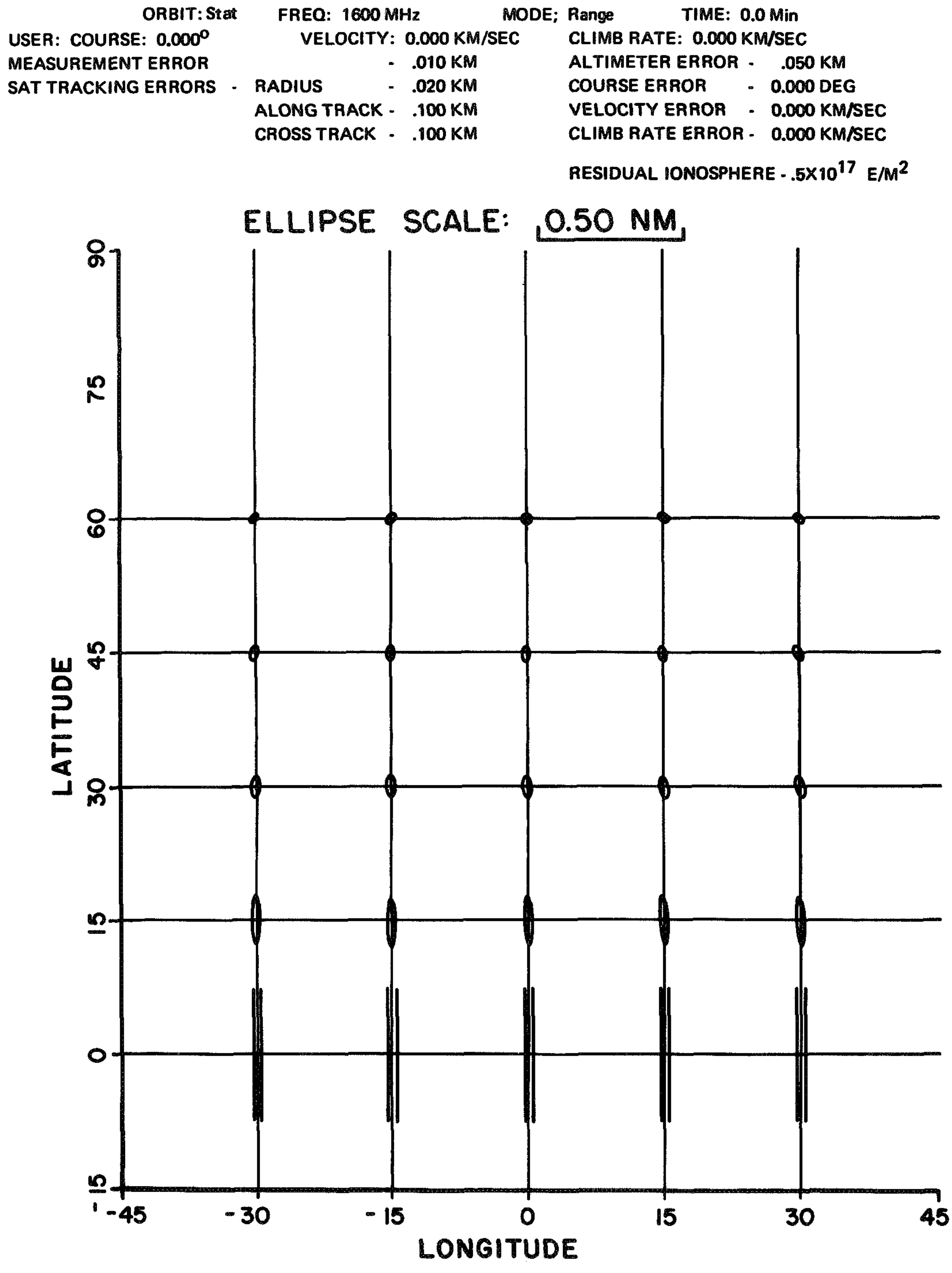

Figure 6.- Error ellipses for L-Band spherical ranging. Satellites in geostationary orbit with sub-longitudes at ±30°. Error inputs are all 1σ values.

LARGE SATELLITE

ACTIVELY STABILIZED/EARTH POINTING ANTENNA

GEOSTATIONARY ALTITUDE

F D M

LARGE MULTIFEED ANTENNA INITIALLY

LARGE MULTIBEAM PHASED ARRAY EVENTUALLY

Figure 7.- Voice communications satellite

1. 3 TO 6 INDEPENDENTLY TRACKING BEAMS
2. 35 DB PEAK GAIN, CIRCULARLY POLARIZED
3. STEERABLE OVER A ±8.5 DEGREE RANGE IN TWO DIMENSIONS
4. INDIVIDUAL TRANSMITTERS AND RECEIVERS FOR EACH BEAM
5. FIVE WATTS OF RF POWER PER TRANSMITTER

Figure 8.- L-Band voice communications satellite antenna requirements

CARRIER	RANGE CODE	EPHEMERIS/ TIMING DATA	INTERROGATION & ADVISORY DATA	GUARD BAND
.38	.75	.32	.4	.1

Figure 9.- Timing diagram - Satellite transmissions (time in sec)

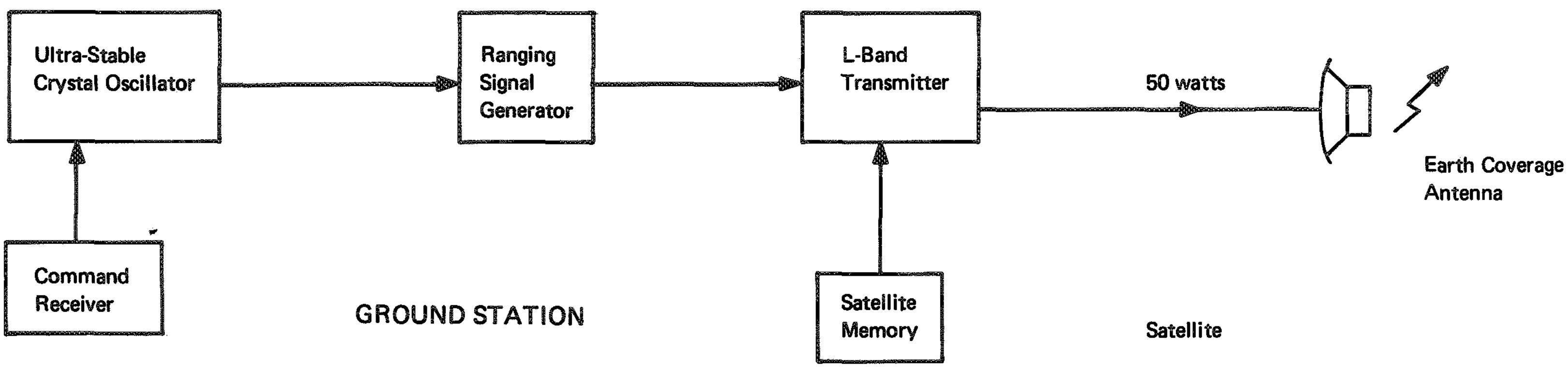

Figure 10.- Satellite equipment

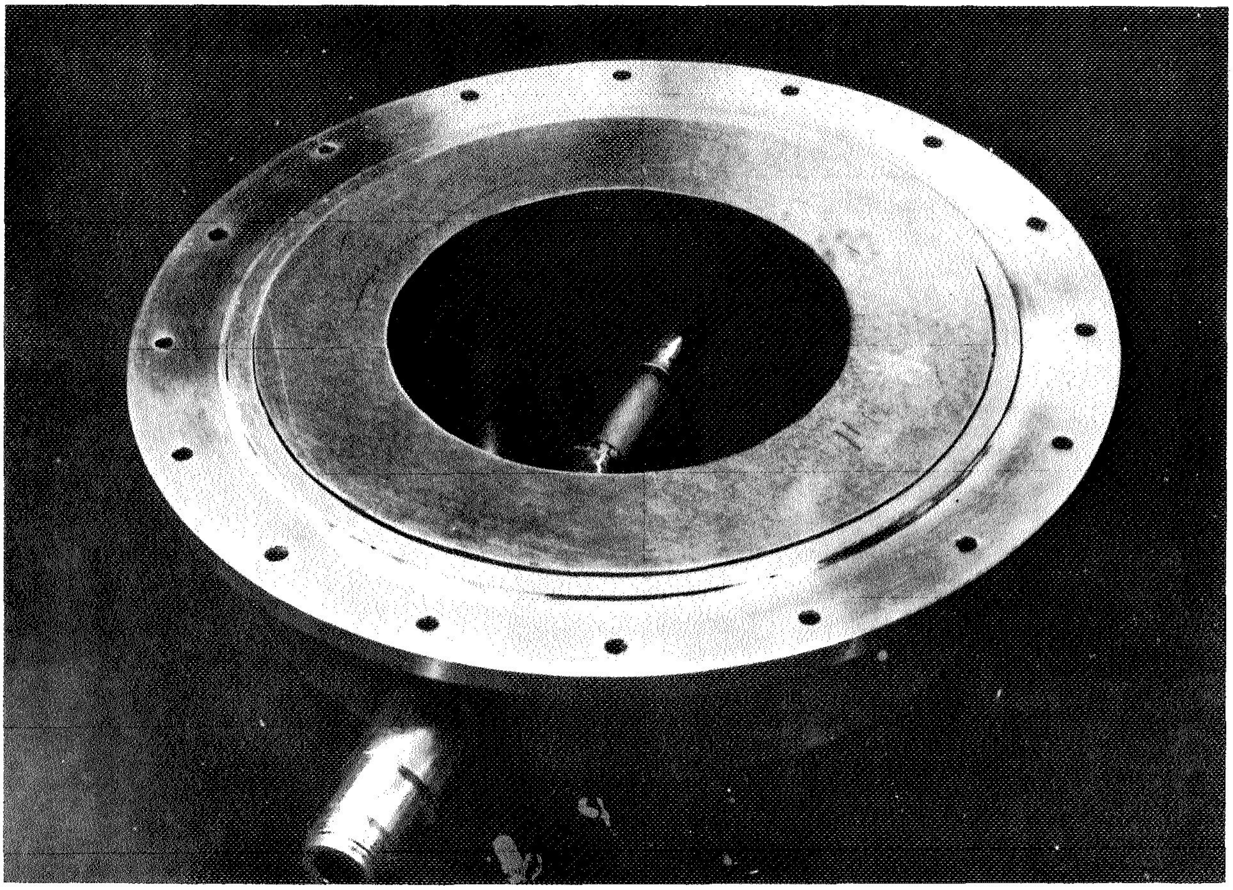

Figure 11.- Orthogonal mode cavity antenna

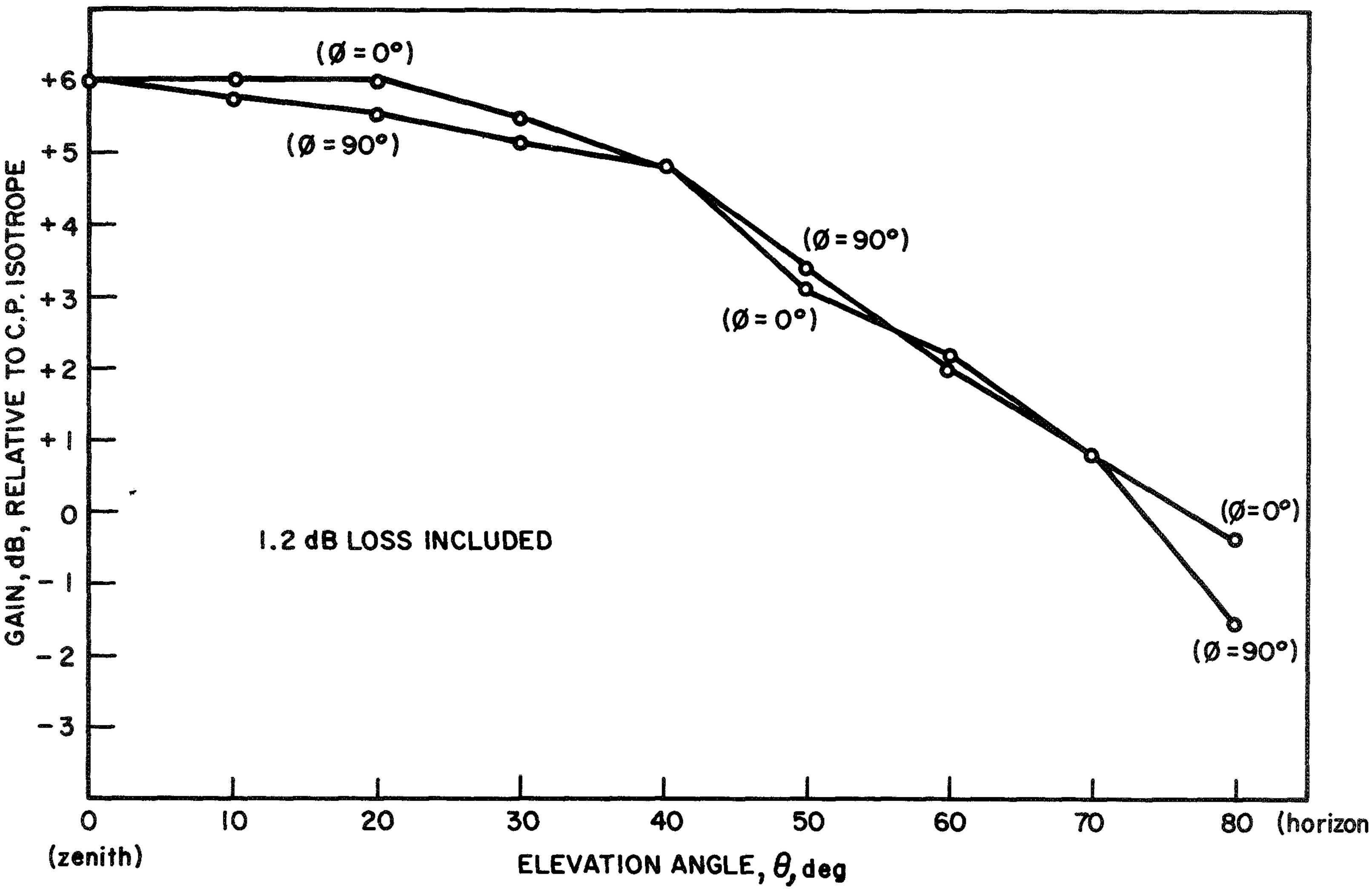

Figure 12.- Principal plane patterns for orthogonal-mode-cavity antenna

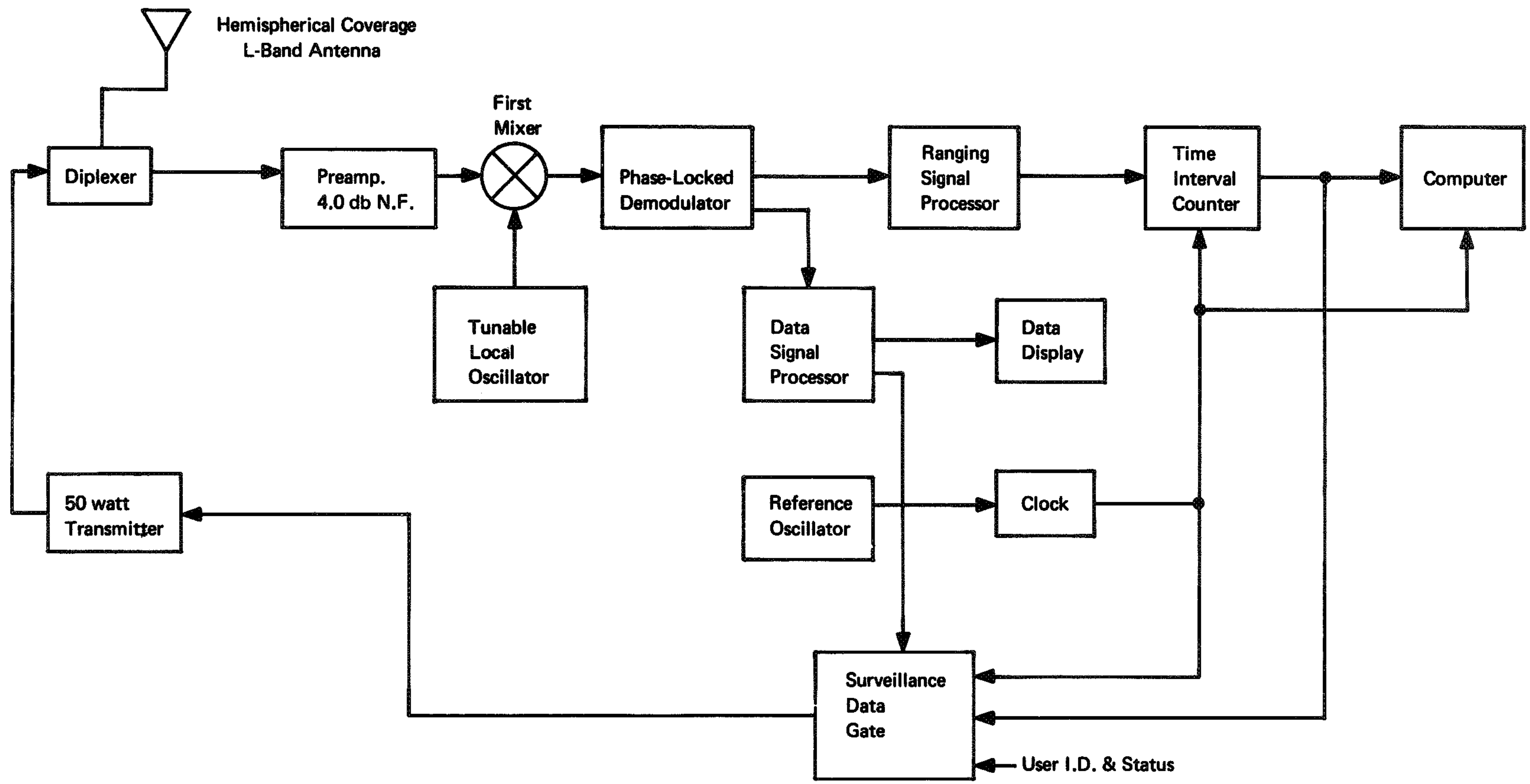

Figure 13.- User equipment

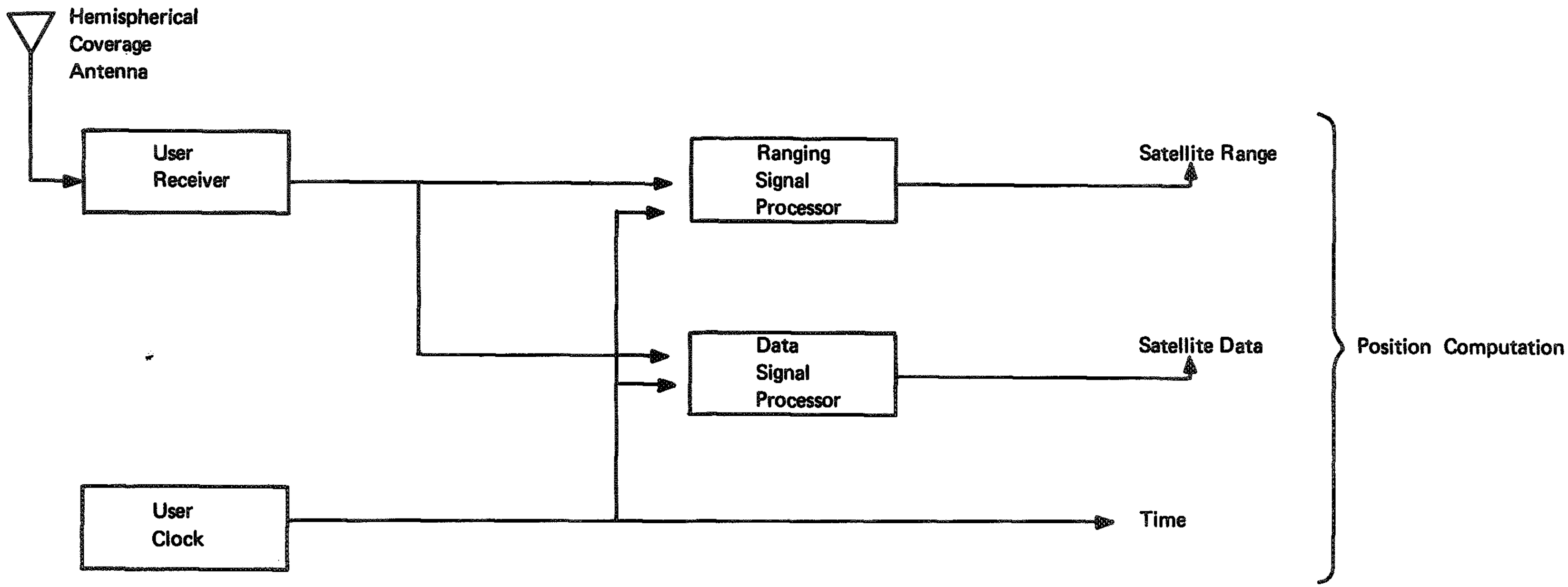

Figure 14.- Position determination function

TABLE I.- NORTH ATLANTIC PRINCIPAL AREA AIR TRAFFIC - FAA ESTIMATE

	1968	1972	1973	1974	1975	1976	1977	1978	1979
SUBSONIC FLIGHTS	91,211	123,000	126,000	137,000	142,000	147,000	152,000	146,000	149,000
SUPERSONIC FLIGHTS	--	--	11,000	13,000	27,000	39,000	54,000	79,000	90,000
TOTAL	91,211	123,000	137,000	150,000	169,000	186,000	206,000	225,000	239,000
DAY/HOUR TRAFFIC									
SUBSONIC									
Busy Day	324	437	447	486	504	522	540	518	529
Peak Hour	33	44	45	49	50	52	54	51	53
Busy Hour	27	36	37	40	40	43	45	43	44
Medium Day	240	325	333	362	375	388	401	385	394
Peak Hour	24	33	34	36	38	39	40	39	39
Busy Hour	20	26	28	30	31	32	33	32	32
Low Day	188	254	260	283	293	303	314	301	307
Peak Hour	19	25	26	28	29	39	31	30	31
Busy Hour	15	21	21	23	24	25	26	25	26
SUPERSONIC									
Busy Day	---	---	34	39	81	117	163	238	271
Busy Hour	---	---	5	6	11	15	21	31	36
Medium Day	---	---	27	32	67	96	133	195	222
Busy Hour	---	---	3	4	9	12	17	26	29
(Ratio of Concorde to Boeing)			1:0	1:0	1:0	1:0	10:1	6:1	3:1
Maximum Instantaneous Load	89	119	127	138	143	157	170	173	181

TABLE II.- VOICE LINK POWER BUDGET — VHF VS L-BAND

	VHF	UHF
Req C/N_o	47.0 dB-Hz	47.0 dB-Hz
Boltz. Const	-228.6	-228.6
Sys. N.T.	31.1 (1300°K)	27.8 (600°K)
Req A/C Power	-150.5	-153.8
Space Att.	166.8 (@125.7 MHz)	188.6 (@1550 MHz)
Atmo/Iono	3.0 (20°el)	0.0
Multipath	5.0 (20°el)	3.0 (20°el)
Pol. Losses	1.5 (20°el)	1.5 (20°el)
	176.3 dB	193.1 dB
Req EIRP	25.8 dBw	39.3 dBw
Sat Edge Gain	13.0 (>earth cov)	22.0 (8°beam)
Min Power Req	12.8 dBw (19W)	17.3 dBw (54W)
Final Amp Eff.	80%	33%
Final Amp Power Req	24W	164W

TABLE III.- RF LINK POWER BUDGET, SATELLITE TO AIRCRAFT WITH LOW GAIN ANTENNA

Transmitter Frequency	1550.0 MHz
Transmitter Power, 50 Watts	47.0 dBm
Transmitter Circuit Losses	1.5 dB
Transmit Antenna Gain	16.0 dB
Effective Radiated Power	61.5 dBm
Path Loss to Subsatellite Point	187.3 dB
Position Loss	5.0 dB
User Antenna Gain	2.0 dB
Polarization Loss, Circuit Losses	1.5 dB
Received Carrier Power	-130.3 dBm
User System Noise Temperature	500.0 oK
Receiver Noise Power Density	-171.6 dBm
Carrier to Noise Density Ratio	41.3 dB-Hz

TABLE IV.- PRELIMINARY WEIGHT AND POWER ESTIMATES
FOR POSITION REPORTING SATELLITE

	Power Req. (W)	Weight Estimate (Lbs)
Structural Subsystem	-	51
Attitude Subsystem	2	17
Positioning Subsystem	50	62
Telemetry and Command	25	25
Electrical Integration	6	20
Power Control	25	70
	108	245
Required Power for 5-Year Life (20% Degradation)	135	
Required Power if Equatorial Orbit	147	

TABLE V.- DIGITAL DATA BURST

Identification	45 Bits
Range Measurement	80 Bits
Time	20 Bits
Status Information	55 Bits
	200 Bits

TABLE VI.- PRELIMINARY WEIGHT AND POWER ESTIMATES FOR DATA COMMUNICATION AND POSITION DETERMINATION SATELLITE

	Power Req. (W)	Weight Estimate (Lbs)
Structural Subsystem	-	75
Attitude Subsystem	14	25
Positioning & Data Subsystem	108	71
Telemetry & Command	25	25
Electrical Integration	7	40
Power Control	60	172
	214	408
Req. Power for 5-Year Life (20% Degradation)	268	
Required Power if Equatorial	292	

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